InLCA: Case Studies – Using LCA to Compare Alternatives

LCA of Ex-Situ Bioremediation of Diesel-Contaminated Soil

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Abstract

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Goal and Scope. Primary and secondary environmental impacts associated with bioremediation of diesel-contaminated sites were assessed using a retrospective life cycle assessment (LCA) as a function of the duration of treatment and the achievement of regulatory criteria. The case study consisted of the remediation of diesel-contaminated soil using biopiles of 8,000 m^3 of subsurface soil impacted with an average of 6,145 mg of diesel fuel/kg soil over a two-year period.

Methods. Two scenarios were compared; the construction of a single-use treatment facility on site or the use of a permanent treatment center that can accept 25,000 m^3 soil/year. Moreover, since bioremediation is never 100% efficient, different efficiency scenarios, including the transportation of partially treated soil to landfill were analyzed. The primary impact of residual soil contamination was determined by developing a specific characterization factor (ecotoxicity and human toxicity categories in the EDIP method) based on the toxic components of diesel. Secondary impacts were assessed with an LCA software.

Results and Discussion. One major observation was the fact that the soil itself is responsible for an important fraction of the system's total impact, suggesting that it is beneficial to reach the highest level of remediation. The reutilization of the treatment facility is also an important issue in the overall environmental performance of the system. In the case of a single-use treatment center, the analysis showed that site preparation and site closure were the major contributing stages to the overall impact, mainly due to the asphalt paving and landfilling processes. Results indicated that off-site transport and the biotreatment process did not contribute notably to the level of environmental impact. The use of a permanent treatment center is preferred since it allows a significant decrease of the secondary impact. However, when soil had to be transported for a distance greater than 200 km from the site, global impacts increased significantly.

Conclusion. Results from this study allowed identifying several process optimizations in order to improve the environmental performance of the biopile technology including: the achievement of low level of residual contaminants, the minimization of asphalt or the use of a permanent treatment center.

Recommendation and Outlook. LCA was found to be an efficient tool to manage contaminated soil in a sustainable way. However, because of the major contribution of residual soil contamination, additional spatial and temporal data should be collected and integrated in the substance characterization models.

Keywords: Bioremediation; contaminated soil; EDIP method; life cycle assessment; primary impact; secondary impact

Introduction

Hazardous waste management has received attention in both Canada and the United States, namely for sites posing threats to public health. It is estimated that the number of contaminated sites in North America is over 425,000 (GAO 1997). Across Canada, close to 4,800 contaminated sites lie abandoned or underutilized and about 60% of these sites involve petroleum hydrocarbon contamination (Treasury Board of Canada 2002). Soil contamination from leaking underground storage tanks and its adverse effects are major problems today due to their widespread distribution. Their current condition causes health and economic burdens. By July 2002, the Quebec (a province of Canada) Ministry of Environment's database on contaminated sites included 1893 sites contaminated with petroleum hydrocarbons (Environnement Québec 2002). Therefore, huge volumes of soil need to be treated and the cost will appear very high to society. National and provincial policies have forced owners to decontaminate to certain criteria such polluted soils. Hence, in the province of Quebec, three thresholds for site use have been set out for petroleum hydrocarbon (C_{10}–C_{50}) contamination; A (300 mg/kg) for residential use; B (700 mg/kg) for commercial use and; C (3,500 mg/kg) for industrial use (Environnement Québec 2002).

Remediation using aboveground biotreatment is the most cost-effective approach for hydrocarbon-contaminated soils (USEPA 1995). Aboveground biopiles are now widely used to reduce the concentration of petroleum constituents in excavated soil through the use of biodegradation (USEPA 1995). This technology can be used on site or at a permanent treatment center. Basically, it involves excavating the contaminated soil, removing the debris, heaping soils into piles and stimulating aerobic microbial activity within the soil through the aeration, addition of nutrients and moisture. The enhanced microbial activity results in degradation of soil-sorbed petroleum-product in CO_2 and water. Advantages of this technology include relatively low operating costs, simplicity of operation and design and relatively high treatment efficiency compared to *in-situ* technologies (USEPA 1995). Some disadvantages include the duration of treatment, which can go from 6 to 24 months, and the non-achievement of low levels of contamination (e.g. the Quebec 300 mg C_{10}–C_{50}/kg A criterion). Soil remediation has often focused on a single perspective: reducing concentra-

tions below a given criteria so that a high soil quality can be restored. Experience has shown that this objective is difficult to achieve. One of the characteristics of all biotreatments is that it is almost impossible to reach complete decontamination, therefore a residual contamination always remains. Moreover, bioremediation (and clean-up operations more generally) can lead to a transfer of local contamination from soil to other compartments through the use of resources, materials and energy. The best compromise between the environmental positive and negative impacts can hence be guided by decision criteria to select a remediation technique. In this perspective, life cycle assesment (LCA) is an effective tool. A number of impact assessment methodologies are available to the LCA practitioner. These methods include a model for each impact category. Traditional impact categories in LCIA methods include those from a global level, such as climate change and ozone depletion, regional level impacts such as acidification and local level impacts, including photochemical smog formation, ecotoxicity and toxicity.

Only a few LCA studies have been conducted on remediation of contaminated sites. In all cases, the remediation process itself generates environmental impact (Beinat et al. 1997, Bender et al. 1998, Diamond et al. 1999, Page et al. 1999, Volkwein et al. 1999). This generated impact can be of global or local scale and can be classified as secondary impact (Volkwein et al. 1999). On the other hand, primary impact refers to the local impact caused by the contamination in soil. Beinat et al. (1997) first used LCA to compare four remediation alternative techniques for contaminated soil in the REC (Risk Reduction, Environmental Merit and Costs) project. REC is an holistic approach that combines the economic, social and environmental costs of a remediation project. In the Diamond study (Diamond et al. 1999), six qualitative LCA (called Life Cycle Management in the paper) covering no action, encapsulation, excavation and disposal, vapour extraction, *in-situ* bioremediation and soil-washing were performed. From that study, the general framework for using LCA for site remediation was clearly explained, specifically the issue related to the functional unit and the impact assessment. Diamond et al. showed the transfer of contamination from contaminated site to off-site impacts such as land consumption and impacts related to emissions. The study's conclusions are that LCA is a good tool to minimize the environmental impacts of remediation activities. The quantitative LCA performed by Page et al. (1999) was done on the remediation of a lead-contaminated site by excavation and disposal. Along with a complete assessment of secondary impacts, the site-related human toxicity impacts were evaluated following Diamond's framework and using a generic exposure approach model and comparison with an effect level. This study highlighted the remediation life cycle stages that generated significant environmental impact over the three regional scales: global, regional and local. Volkwein et al. (1999) compared primary and secondary impacts with both a risk assessment and a streamlined LCA. Three remediation alternatives were analyzed and compared with the help of disadvantage factors. Conclusions from these studies indicate that LCA methodology (especially the impact assessment phase) requires further refinement to be used in site remediation assessment. None of these studies followed ISO14042 recommendations specifically (characterization, normalization and weighting), nor did they use a complete LCIA method. Nonetheless, stakeholders need simple tools to implement LCA in a remediation strategy, such as a commercial LCA software and LCIA method (like the SimaPro software and the EDIP method used in the present study). Finally, these studies did not use LCA to assess primary impacts, which limits the comparison between primary and secondary impacts.

The present LCA study analyzes the remediation of a diesel-contaminated site using an aboveground biopile technology. All inputs and outputs are compiled and the impact of the entire activity as well as for each of the different stages is assessed. Since the effects of bioremediation activities extend beyond the contaminated site itself some questions arise. For example: Are the secondary impacts generateted increased in relation with the increase in regulatory criterion severity? From a management perspective, does a permanent treatment center offer a better alternative than a single-use treatment facility? In what area can we improve the overall performance of this technology? Is the LCA method really useful to assess the environmental performance of site remediation? The findings of this study have allowed to answer the questions stated above as well as to propose ways to improve this popular technology.

1 Goal and Scope Definition

The case study considered is a diesel-contaminated site (16,900 m²) located in the province of Quebec (Canada). A volume of 8,000 m³ was impacted with petroleum hydrocarbon. The petroleum hydrocarbon (diesel oil) contamination resulted from the leakage of a diesel storage tank. This contamination (6145 mg C_{10}–C_{50}/kg soil) expressed in terms of the summation of hydrocarbon fractions from 10 to 50 carbons was well above the accepted C and B regulatory criteria and therefore had to be removed. The remediation project consisted basically of excavating the soil and treating it using an aboveground biopile treatment. The target was 700 mg C_{10}–C_{50}/kg soil (Quebec's B criterion).

The main objective of this LCA was to compare the primary and secondary impacts of the biopile treatment's life cycle as a function of the duration of treatment and the achievement of regulatory criteria. A single-use facility (the initial case study) was compared to a permanent facility to determine which parameters influence the environmental performance of each alternative. These results would also allow the proposal of some optimization processes to reduce the environmental load of the bioremediation treatment.

The functional unit was set according to Diamond's (1999) recommendation that, "the functional unit should relate to the production of an amount of treated soil". Based on this, the functional unit selected for this study was defined as "the remediation, during a two-year period, of 8,000 m³ of diesel contaminated-soil (6145 mg C_{10}–C_{50} / kg) to the B generic criterion (700 mg C_{10}–C_{50} / kg) with an aboveground biopile treatment". The reference flow was 8,000 m³ of soil.

2 Methods

The LCA was performed according to the set of rules established by ISO (ISO 14040, 14041, 14042 and 14043).

2.1 Life Cycle Inventory (LCI)

2.1.1 System description

The environmental load was calculated in relation to the functional unit, and the inventory results are presented, evaluated and distributed into 11 life cycle stages as shown in the site remediation life cycle shown in **Fig. 1**. Each of the 11 life cycle stages (such as soil excavation, biopile treatment, leachate and volatile emission management, backfilling the excavation hole with treated or clean soil) is composed of one or several processes, which can be material production, transportation or equipment operation.

A scenario was established in which the remediation was not successful in reaching the B criterion. In this case, partially treated soil (concentration > B criterion) are brought to a landfill (Fig. 1). Transportation modules are included in the process stages. Transportation involves changing the location of the soil and materials used.

Numbers between brackets in the following paragraph refer to the stage number in Fig. 1. Site preparation (1) includes the installation of an enclosure around the contaminated site and decontamination area; two shelters for nutrients and equipment; paving of the treatment area (with four successive layers of asphalt, gravel and clay) and preparation of the biopiles containment (with a 0.5 mm thick LDPE cover) (**Fig. 2a**). Five biopiles were then constructed similarly to windrow composting piles (4) (Fig. 2a). They consisted of long rows of soil 1.5 m high and 50 m long that were placed (4) on the impermeable barrier installed in stage 1. The biopiles were aerated and irrigated with water from the leachate system (10) and nutrients (urea and di-ammonium phosphate) until remediation objectives were achieved (**Fig. 2b**). The aeration system installation (3) requires the installation of PVC pipes

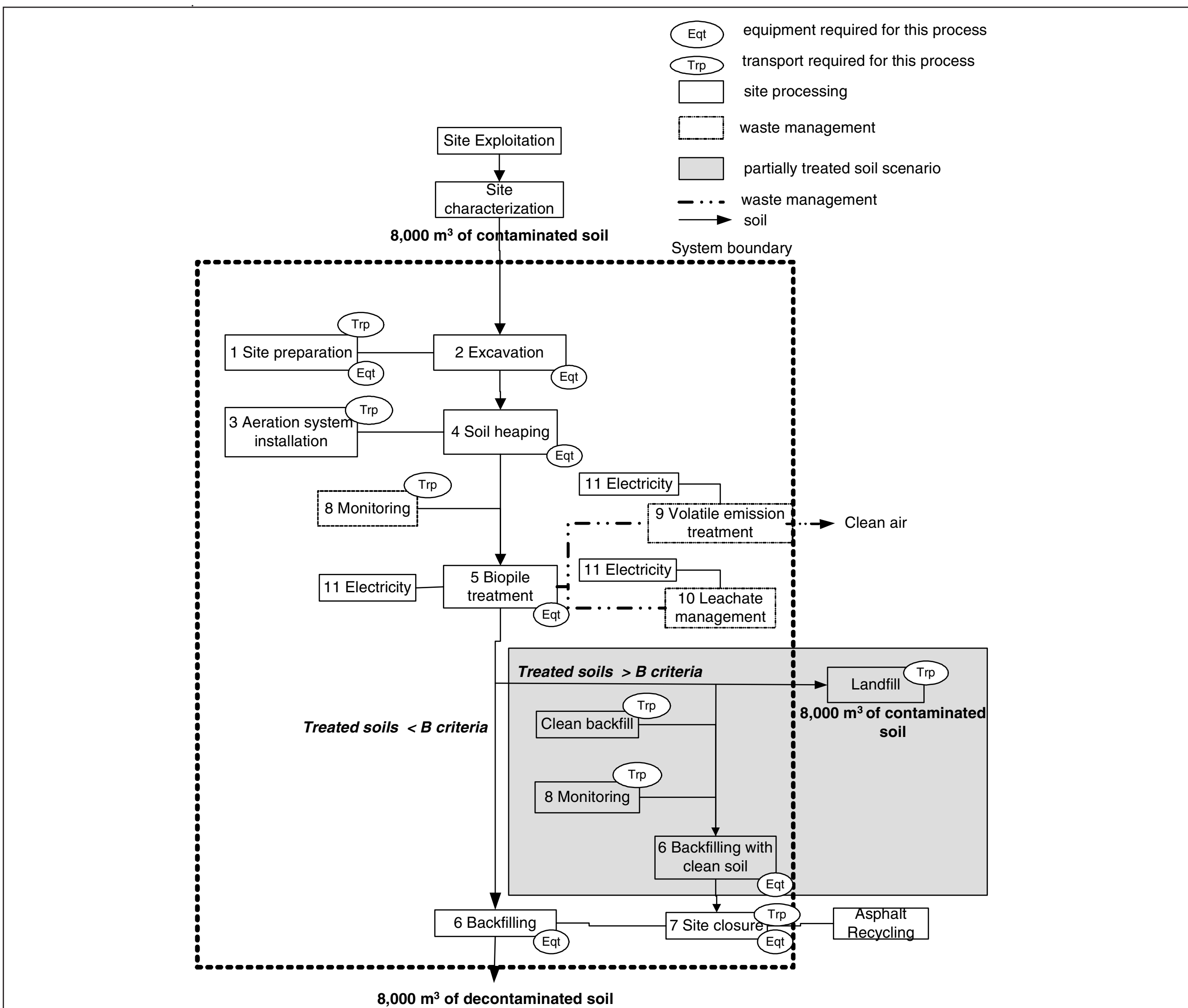

Fig. 1: Life cycle flow diagram

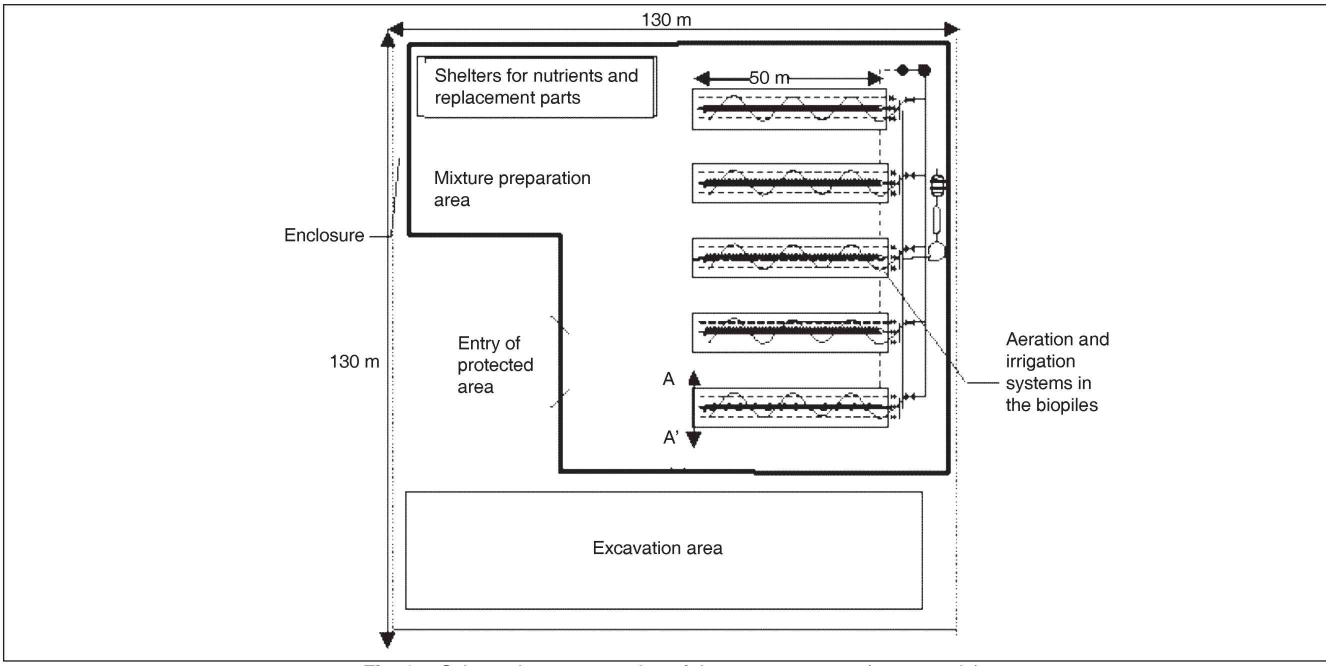

Fig. 2a: Schematic representation of the treatment area (not to scale)

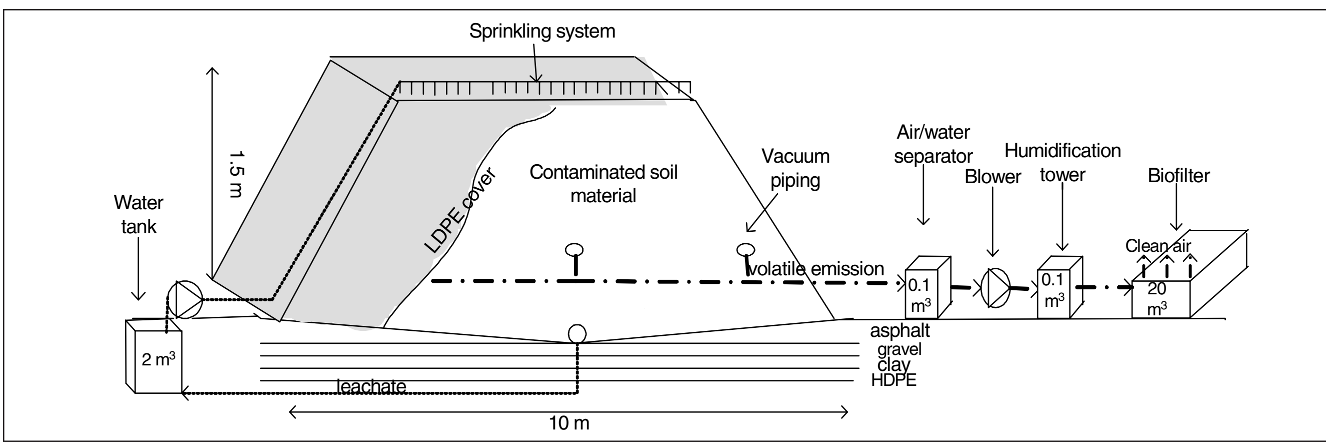

Fig. 2b: Schematic representation AA' of the biopile soil treatment technology (not to scale)

before heaping the soil (4). An air/water separator, humidification tower and air biofilter allowed the clean-up of volatile emissions (9) while a water holding tank store the leachates which were then used to irrigate the biopiles (10). Stages 2, 4, 5 and 6 consist in the use of an excavator to move the soil before, during and after treatment. Site closure (7) involves the dismantling of all structures on the site using the appropriate equipment and sending the wastes to specific landfills (SimaPro databases possess the landfill life cycle for several kinds of wastes). No consideration was made to the *in-situ* treatment of groundwater. This treatment facility was located near the contaminated area and had to be removed at the end of decontamination (Fig. 2a).

2.1.2 Data collection

The data collection for this study was carried out from the results obtained from the site owner and by modeling the technology (Bage 2002). Physical design (biopile dimensions, quantity of nutrients provided) was developed according to the recommendations of von Fahnestock et al. (1998). Moreover, the assessment of the quantity of oxygen required for biodegradation to occur in the contaminated soil allowed several calculations such as the quantity of air needed for biodegradation, the air discharge in the pipes, the length of pipes, the pressure drop in the pipes, pump power and finally, the quantity of electricity required. Other calculations allowed the identification of the dimensions of the humidification tower, biofilter and water tank. Thus, primary data come from the design calculations realized for the installation of the treatment area and its subsequent processes (Bage 2002). Because of the lack of suitable Canadian LCI data at the time of the study, secondary data from commercial databases such as Buwal, ETH, Franklin and IVAM databases, available in SimaPro, were also used (Pré Consultants 1997). US data from Franklin database were privileged when possible. The LCA modeling was performed using SimaPro 5 LCA software.

2.1.3 Postulates

To conduct an LCA, it is necessary to establish some postulates; otherwise, the study could be endless. The main assumptions used in the elaboration of the LCI are the following:

- The duration of the site remediation from the beginning of soil excavation to the site's closure was set at 2 years including a shutdown period of four months in winter (Bage 2002).
- Geographically, the contaminated site is located in Eastern Canada, however, the overall system boundaries include all related activities that are in the SimaPro databases and which are essentially based on data from Western Europe. Some data were also obtained from the U.S. Franklin database.
- All activities occurring in the case study were included except the ones related to staff activities.
- The electric energy consumption considered was for the use of pumps utilized for aeration of the biopile, and management of liquid and gas emission. The Quebec power grid mix (comprised of 93% hydroelectricity, 2% nuclear, 1% thermic, 4% others) was built with ETH and IVAM data.
- All transportation to and from the site was included (equipment, soils, samples for analysis). The distances were set at 150 km for the equipment, 200 km for the laboratory and the landfill. The emissions from trucks and mechanical equipments were calculated using emission factors appropriate to the type of vehicle, loading and fuel type. Equipment use was simplified to include only the intended use of the equipment therefore; on-site traffic was excluded from transport.
- *Ex-situ* monitoring activities (laboratory analyses) were not taken into account due to their minor role (Diamond et al. 1998) however, transportation of samples to the laboratory was included.
- Landfilling of soils was excluded from the system boundary (Fig. 1), the reason being that within the LCA's temporal boundary, it is likely that the landfill would remain open and no significant emission to the environment would occur (Diamond et al. 1998). Nevertheless, landfills for the waste management operations were included in the system through the SimaPro databases. From dismantling after treatment, seven types of wastes were generated and sent to landfills (whose life cycles are already included in the software's databases): HDPE, LDPE, aluminium, asphalt, steel scrap, wood and glass. Each type of waste was associated with a certain type of landfill except for asphalt which was attributed to 'landfill for other materials'.
- The asphalt used for the pavement (786,000 kg; 0.1 m thick) of the treatment area is virgin and 50% of the asphalt that is removed from the pavement at the end of the treatment is recycled. Therefore, only 50% of the asphalt will end up in a landfill. Recycling asphalt was not included in the system since the recycled asphalt would be produced off-site (crushing and transport were included) and would have a different ultimate end use. A product avoided credit was then added to the system since it avoids the production of 393,000 kg of virgin asphalt. Moreover, due to the high environmental impact of asphalt production, asphalt paving was deliberately restricted to the contaminant sensitive parts of the treatment area: the foundation of the biopiles (2,500 m^2) and the soil storage area (900 m^2).

More than 1.9E+06 kg of materials was required to build the treatment center (**Table 1**). The two major mass inputs were clay (880,860 kg) and asphalt (786,000 kg). Pumps required 9,400 KWh during the two years of operation. Transports represented 98,000 km and the total diesel consumption (equipment and transport) calculated for these 2 years was 95,000 kg, which surprisingly is equivalent to the diesel that leaked into the soil and caused the initial contamination (91,000 kg). When soils had to be landfilled (e.g., when the treatment was not successful in reaching B criterion), this diesel consumption rose to 140,000 kg.

Table 1: Principal materials involved in the building and operation of a soil treatment center

Inputs	Mass (kg)	Life cycle stage
Aluminum	151	(1) Site preparation
Asphalt	786,000	
Clay	880,860	
HDPE	14,367	
LDPE	1,840	
Steel	25,644	
Wood	4,904	
Zinc	4	
Diammonium phosphate	1,644	(4) Soil heaping
Urea	7,525	
Wood chips	189,600	
Glass	552	(8) Monitoring
Latex	5	
Water	40,486	
Gravel	4,275	(9) Volatile emission treatment
Manure	6,402	
Peat	15	
PVC	11,473	(3) Aeration system installation (9) Volatile emission treatment
Total	**1,975,547**	

2.2 Life Cycle Impact Assessment (LCIA)

This phase of the LCA serves to evaluate the significance of the environmental interventions contained in the LCI. To conduct an LCIA, it is necessary to select an impact assessment methodology which regroups the different characterization models for each impact category. These characterization models allow the calculation of characterization factors (CF) which express the measured substance's strength relative to a reference substance. At the time of the study (2000), no method was available that integrated Canadian specificities, the choice of model depended primarily on model transparency and simplicity, especially given the fact that

new characterization factors would have to be calculated for some substances. It was finally decided to choose the Danish EDIP (Environmental Design of Industrial Products) method (Hauschild et al. 1997, Wenzel et al. 2000). This method appeared to be the most appropriate LCIA method thanks to its transparency (Sorensen 2002) and its widespread use in European LCA case studies. Since the objective was to compare different types of impacts (i.e. primary vs. secondary impacts), it was necessary to normalize the category indicators to better understand the relative magnitude for each impact category (ISO 14042, 2000). No normalization values were available for the Canadian context at the time of the study: the default (Danish) values of EDIP97 were therefore used. Similarly, EDIP97 default weighting values were used to calculate single scores. The impact assessment calculations are fully computerized by the SimaPro LCA software (in selecting the EDIP method) and will not be discussed here. For more details on the EDIP method and models, see Hauschild et al. (1997) and Wenzel et al. (2000). The twelve environmental relevant impact categories considered in the impact assessment are: global and regional impact categories: climate change, ozone depletion, acidification, eutrophication and photochemical smog; local impact categories: ecotoxicity water acute, ecotoxicity water chronic, ecotoxicity soil chronic, human toxicity air, human toxicity water, human toxicity soil and bulk waste.

To determine the primary impacts of the soil contamination prior and after treatment, we had to assess impacts generated by the diesel in the soil. Since characterization factors for diesel are not available in SimaPro, it was decided to calculate the characterization factors for the diesel from the EDIP methodology (Hauschild et al. 1998, Wenzel et al. 2000) for each local impact category (ecotoxicity and toxicity). According to EDIP model for ecotoxicity and toxicity impact categories, characterization factors (CF) are determined as the product of several factors which represent the substance dispersion in the environment, its ecotoxicological characteristics and its biodegradability (Equations 1 and 2):

$$CF_{ecotoxicity} = f \times ETF \times BIO \tag{1}$$

$$CF_{toxicity} = f \times I \times T \times HTF \times BIO \tag{2}$$

where f is the final distribution between different compartments (water, soil, air), ETF is the ecotoxicity factor in different compartments, BIO is a biodegrability factor, T is an efficiency transfert and HTF is a human toxicity factor when consumed or inhaled. For more details about these calculations see Wenzel et al. (2000).

Since diesel is a mixture of hundreds of chemical compounds, characterization factors were calculated for the three main fractions (C_6–C_{10}, C_{11}–C_{16} and C_{17}–C_{21}) representative of diesel for toxicological and ecotoxicological impact categories (Gustafson et al. 1997). These characterization factors were then entered in the software in order to proceed with the impact assessment of the primary impact. This allowed the primary impacts to be accounted in the assessment of life cycle impact of the biopile bioremediation. Hence, by subtracting the overall impact of the remediation project from the secondary impacts, it became possible to track the primary impacts reduction associated to the soil contaminant.

3 Results

3.1 Impact assessment

The secondary impacts related to the site remediation were assessed and presented as a single score (in points), meaning that the impact is normalized, weighted and aggregated according to EDIP method.

3.1.1 Quantification of primary impact

The efficiency of treatment can vary highly depending on the type of soils (e.g., percentage of clay), the presence of inhibitory substances (e.g., heavy metals), the concentration and activity of microorganisms involved in the degradation and the heterogeneity of the contaminant and nutrient distribution. Because biopile technology is never 100% efficient, it means that residual contaminants are always present. Depending on the efficiency of the treatment, it is often mandatory to dispose the partially treated soil in a landfill. Hence, a scenario in which the partially treated soil is transported to a landfill was analyzed (Fig. 1). In this scenario, the three remediation targets (A, B and C generic criteria) were compared based on the summation of primary and secondary impacts as well as on the secondary impact itself. (**Fig. 3**). When only the secondary impacts of the whole life cycle are considered, results indicate that reaching criteria B and A generates an increase of 3% (difference between 1,063 points for B criterion and 1,095 points for C criterion) in comparison to sending all the soil to landfills (e.g., reaching the C criterion) (Fig. 3). This small difference is due to the predominant impact associated to site preparation and site closure which are unavoidable for reaching the three targets. On the other hand, the contribution of the additional energy, water and nutrients required is very low compared to site preparation. Even if transportation of semi-remediated soil to landfill and transportation of clean soil for backfilling represent a total travel distance of 85,500 km, this related impact was hidden by the site preparation and site closure stages and by the increase in electricity and nutrients quantity required to reach B and A criteria. Adding the primary to the secondary impacts allows for a more accurate representation of the overall impact of the bioremediation as well as visualizing the specific effect of the contaminant (C_{10}–C_{50}) in the reference flow. It can be observed that the presence of contamination has a very important contribution on the overall impact. The initial contaminated soil possesses a residual impact of 18,576 points, which represents about

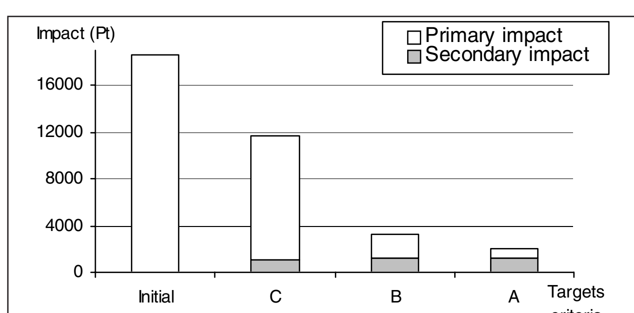

Fig. 3: Remediation impact (single score) where A, B and C are the Quebec's soil remediation criteria (C= 3500 mg C_{10}–C_{50}/kg, B = 700 and A = 300)

ten times the number of points generated by the remediation activities. Obviously, reaching low levels of contamination (A and B generic criteria) contributes to the minimization of the residual contamination and, thereby, to the decrease of the bioremediation's total impact (Fig. 3). Reaching the B criterion (700 mg C_{10}–C_{50}/kg) implies that the presence of residual contaminant increases the remediation impact by about 182% while it is only increased by 77% when the A criterion (300 mg C_{10}–C_{50}/kg) has to be reached. However, achieving these low levels of contamination requires much more time which translates into higher costs for stakeholders. Moreover, the contribution of the bioprocess itself was assessed. Hence, life stages 5, 8, 9, 10 and 11 representing respectively, the biopile operation, the treatment of leachate and gas emission, the monitoring activities and the electricity consumption were analyzed. The bioremediation process itself (without any peripheral processes such as excavation, heaping soils or site preparation) generates only 4% of the total impact (46 points on 1,164 points) and remains the same whatever the remediation target. Once again, the difference in the quantity of electricity, nutrients and water used is not significant.

3.1.2 Quantification of secondary impact and process optimization

More than 214 substances have contributed to the secondary impacts generated by the soil treatment, but only 12 of these contribute to more than 1% of the total impact (**Table 2**). The most important output is 'final wastes' which, with 4.0E+5 kg, contributes, through the bulk waste category, to 28% of the total impact. These final wastes are emitted during the site closure stage and contribute to 75% of the impact of this stage. They are the only outputs of the process 'landfill other material' where 393,000 kg of asphalt is sent. Final wastes have a characterization factor of 1 for the bulk wastes category. Other wastes (from landfills in which aluminum, HDPE, wood and others are sent) have the same characterization factor but are in lower quantity. The significant quantity of asphalt (393,000 kg) sent to landfills explains the high level of impact of the site closure stage and of its sub-process 'landfill other material'. During site closure, some solid wastes are released but waste management (including recycling of asphalt) also allows a net environmental benefit at this stage for acetone, benzene, CO_2 and other substances (Table 2). The waste named 'unspecified' corresponds to some wastes emitted during another waste management process 'landfill for wood'. Sr is the other main output of the system (contributes to 15% of the total impact) and is emitted during the site preparation stage. These 5.27 kg of Sr come from the steel life cycle which is used during shelters, enclosure and water tank installation sub-systems (Fig. 3). With 6.2E+05 kg, CO_2 emissions represent only 8.27% of the total impact. The impact of CO_2 is partially hidden by the values of normalization of the climate change category. CO_2 is emitted during equipment and transport processes.

Fig. 4 shows the partitioning of the impacts according to the different life cycle stages of the biopile treatment system. The total impact is essentially generated by the bulk waste impact category (43% of the total impact). Wastes are emitted during the site closure stage and specifically during the waste management processes. Only two stages of the system were determined to be significant: site preparation (1) and site closure (7). 49.6% of the total impact was generated by the site preparation (enclosure and shelter installation, biopile containment, asphalt paving and clay spreading). Asphalt paving and shelter installation are the two major processes contributing to the site

Table 2: Substances released into the environment (contributing to more than 1% to the total impact of the system)

Substance	Mass (kg)	Impact categories for which the substance is characterized	Total	(1) Site preparation	(2) Excavation	(3) Aeration system installation	(4) Soil heaping	(5) Biopile treatment	(6) Backfilling	(7) Site closure	(8) Monitoring	(9) Volatile emission treatment	(10) Leachate management	(11) Electricity
			100.0	49.6	0.9	4.4	0.9	0.9	1.0	41.0	0.3	0.15	0.8	0.2
Airborne emissions														
Acetone	3.8E-02	Photochemical smog, toxicity	1.0	1.4	x	x	x	x	x	–0.4	0.0	0.0	0.0	0.1
Benzene	4.2E-01	Photochemical smog, toxicity	4.5	6.7	0.0	x	0.0	0.0	0.0	–2.2	0.0	0.0	0.0	0.0
CO_2	6.2E+05	Climate change	8.3	6.4	0.4	0.3	0.4	0.4	0.6	–0.1	0.0	0.0	0.1	0.0
Hg	2.9E-02	Eutrophication, toxicity	1.4	1.5	0.0	x	0.0	0.0	0.0	–0.1	0.0	0.0	0.0	0.0
NOx	2.0E+03	Eutrophication, acidification	2.4	1.5	0.1	0.2	0.1	0.1	0.1	0.2	0.0	0.0	0.0	0.0
Pb	7.1E-01	Ecotoxicity, toxicity	2.4	2.3	0.0	x	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Waterborne emissions														
Cd	1.9E-02	Ecotoxicity, toxicity	2.2	1.2	0.2	x	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0
Metallic ions	7.0E+01	Ecotoxicity	3.6	0.3	0.0	2.7	0.0	0.0	0.0	0.0	0.2	0.0	0.4	x
Sr	5.3E+00	Ecotoxicity	15.1	14.9	x	x	x	x	x	–0.2	0.2	0.0	0.1	0.1
Solid emissions														
Final waste	4.0E+05	Bulk waste	30.9	0.2	x	x	x	x	x	30.7	0.0	0.0	0.0	0.0
Unspecified	2.0E+02	Bulk waste	15.3	x	x	x	x	x	x	15.3	x	x	x	x

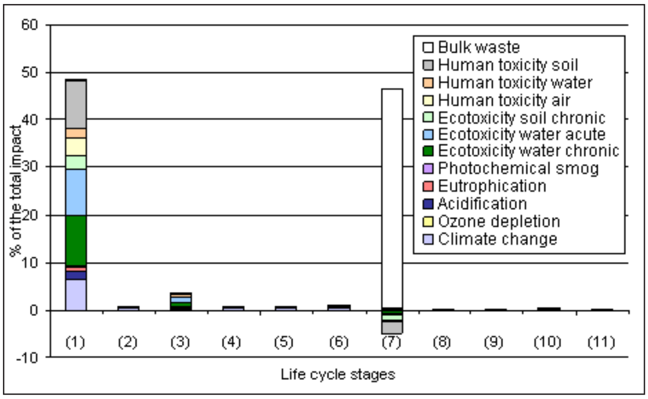

Fig. 4: Contribution of each life-cycle biotreatment stage (single-use treatment center)

Table 3: Impact contribution in percentage of the principal processes (contribution > 5%) of stages 1 and 7

Process	Life cycle stage		
	Entire system	Site preparation (stage 1)	Site closure (stage 7)
Total of all processes	100	100	100
Remaining processes	39.2	59.7	–2.2
Landfill other materials	29.6	NA	73.4
Asphalt mix	16	33	–20.3
Landfill wood	13.9	NA	34.5
Landfill steel	2.0	NA	5.0

preparation impact. Asphalt mix represents 33% of the 'site preparation' impact (**Table 3**). This is because asphalt covers the entire treatment and soil storage surface (3,400 m^2 which represents 786,000 kg) which is necessary to prevent the contaminants from leaching into the soil. The impact of asphalt mix is mainly generated by the electricity and coal cokes needed during its production. With 41.0%, site closure is the second highest contributor process to total impact. Because of the environmental credit associated to the recycling of some materials in the site closure stage, some negative environmental points (benefits on the environment) are credited to this stage (Fig. 4). This stage includes the impact of waste management of residual materials (asphalt, wood, HDPE, LDPE, glass, steel scrap, aluminum). A benefit of –5.4 % is generated by the environmental credit awarded for the recycling of 393,000 kg of asphalt. The landfill where the asphalt is disposed of generates 73.4% of the impact associated to the site closure.

3.1.3 Equipment and transport contribution

Despite their high consumption of diesel and their long work periods (1,639 hours for 2 years of operation), mechanical equipment (dozer crawler and excavators) generate only 6.2% of the total impact (the third score after site preparation and site closure). The dozer crawlers used during asphalt paving and the hydraulic excavators are the equipment that generate the highest impact. This is due to their considerable operation time (166 hours for the dozer crawlers and 300 hours for the excavators), power (315 hp) and diesel consumption (1 l/hp.h). Transport only represents 1.2%.

3.2 Perturbation analysis on the inventory data

To determine which inputs are the most sensitive, a perturbation analysis was performed on the primary data. Except for four inputs (asphalt, clay, steel and processed water), the perturbation analysis did not show any important effect (increase < 0.5%) on any impact category nor on the single score (**Table 4**). Again, the increase in use of asphalt plays a major role on the increase of the ecotoxicity. On the other hand, the increases in use of clay and processed water influence the acidification. These results indicate that special attention has to be paid to the quantity of these materials used in the system. An inaccurate estimation of the value of these inputs could change the final single score in the same order of magnitude.

3.3 Optimization of soil management practices

To optimize soil management practices, three scenarios were studied: The first focuses on the comparison between permanent and single-use treatment centers, the second takes into account the replacement of asphalt by concrete while the last considers the different remediation targets.

3.3.1 Permanent facilities

Instead of a single-use treatment center, soils could have been sent to a permanent treatment site or the single-use facility could have received contaminated soils from other locations. The hypothetical permanent treatment center is able to treat 25,000 m^3 /year during a 10 year period using the same infrastructure. This represents an average size of a treatment center of which there are approximately twenty in Quebec. In these two cases, the impacts generated by the preparation site stage (1) and closure site stage (7) are no longer exclusively allocated to the 8,000 m^3 contaminated soil but to 250,000 m^3 and consequently 85% less impact would have been generated for its remediation. As for a single-use site, local impact would be the main type of impact generated. Aeration system installation (3) is the life cycle stage contributing the most to the total impact (**Fig. 5**). This stage includes the 10,500 kg of PCV required for the pipes needed for the aeration system. Numerous inputs and outputs included in the PVC life cycle generate mainly ecotoxicological and toxicological impact during stage 3; the main output is the substance called 'metallic ions'. 62% of the im-

Table 4: Increased percentages of 5 normalized impact indicators for a 1% input mass increase (only variations >0.5% are presented)

Input increase of %	% Increase for single score and normalized impact indicators					
	Single score	Climate change	Acidification	Human toxicity soil	Ecotoxicity water chronic	Ecotoxicity water acute
Asphalt	0.5	0.0	0.0	0.0	0.7	1.5
Clay	1.2	0.2	1.3	0.0	0.0	0.0
Steel	1.2	0.0	0.0	0.8	0.7	0.0
Processed water	1.2	0.2	1.3	0.0	0.0	0.0

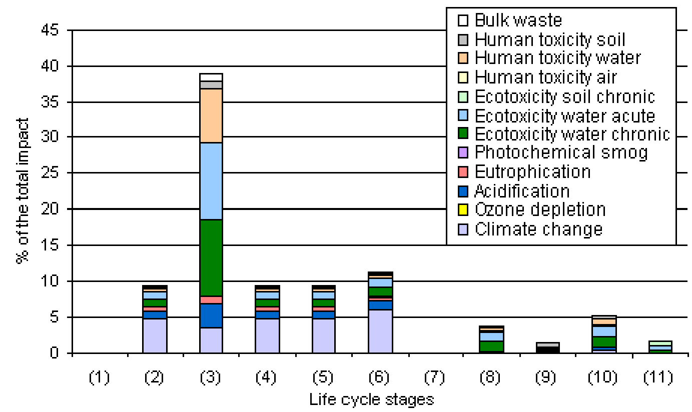

Fig. 5: Contribution of each life-cycle biotreatment stage for a permanent treatment center

pact caused by the aeration system installation comes from the emission of metallic ions (corresponding to 52.5 kg emitted in water) during the PVC life cycle. Stages 2, 4 and 5 entail only the use of an excavator which explains why climate change is the main impact generated in these stages. The backfilling stage (6) requires the same equipment but for a longer duration.

The difference between single-use and permanent treatment centers resides essentially in the transportation of the contaminated soils from the site to the treatment center. It was assumed that the design of the two types of facilities would remain the same. The calculation indicates that the remediation of 8,000 m^3 of contaminated soil in a permanent treatment center would generate less environmental impact than a single-use treatment facility as long as the distance is within a radius of 200 km (**Fig. 6**). This also suggests that a permanent treatment center could deserve a region of about 200,000 km^2.

3.3.2 Asphalt paving scenario

As shown in the previous sections, asphalt is the material input that generates the highest impact during the site preparation and the site closure. One can suggest to replace the asphalt with concrete. However, results indicate that avoiding the use of asphalt reduces the total impact by 66% while the use of concrete increases it by more than 300%. As for asphalt production, the impact generated by concrete production is mainly local (water related ecotoxicity impact categories). It is the production of the energy required during concrete production (especially the generation of electricity from coal) which generates these ecotoxicological and toxicological impacts. It should be noted that the comparison was performed with data from the ETH databases which use the Dutch power grid mix (35% of the electricity from coal (Pré Consultants 1997)). However, in the province of Quebec, 97% of the electricity comes from hydropower and if the concrete was produced there, the impact would be much lower. Replacement of the Dutch power grid mix by the Quebec power grid mix in the asphalt and concrete production processes shows that the use of concrete instead of asphalt would still increase the total impact by 125%.

4 Discussion

4.1 Impact of site remediation

This LCA proved useful to assess the burdens associated with site remediation activity. One major observation was the fact that the contaminated soil itself is responsible for an important fraction of the system's total impact. Even when the soil is remediated to the lowest criterion (criterion A), its toxicity still represents 13% of all secondary impact for the case of a single-use treatment facility. This is because the mass of contaminants (91,000 kg of C_{10}–C_{50}) and the toxicity associated with the petroleum hydrocarbons are very important. It appeared also that treatment efficiency does not influence the level of secondary impact. Nevertheless, on a comparative basis, it is clear that for many cases of site remediation, primary impact will easily exceed the secondary impact associated with peripheral activity. This statement should be used with caution since the EDIP method was used to assess the

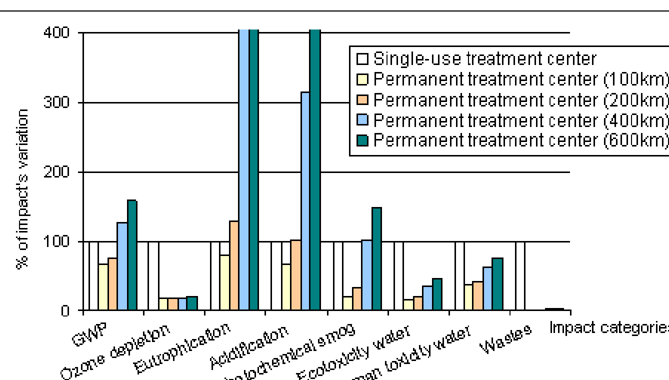

Fig. 6: Impact comparison between single-use and permanent treatment center for 8 impact categories

primary impact. Because EDIP models for ecotoxicity and toxicity impact categories are not multi-media fate models, there is probably an over-estimation of local impacts. Many physical and chemical properties of the soil and the diesel were not taken into account during the characterization factor calculations in the EDIP method. For instance, no sorption phenomena were integrated in the calculations and the model assumes a one-shot release of the contaminant and the entire availability of the diesel (Hauschild et al. 1998). From the EDIP method, all diesel which is in the soil is considered available to produce eco-toxicological and toxicological effects. These omissions probably over-estimate the eco-toxicological and toxicological impact. Moreover, the way to calculate the human toxicity and ecotoxicity factors does not consider the biological environment (are there people, animals or plants near the contaminated site?) nor the type of exposure. The results used in this study are based on these assumptions and omissions but knowledge of site specificities could decrease the relative importance of primary impact. However, the difference between primary and secondary impacts is so large for C and B criteria, that it can be assumed that a more accurate ecotoxicity and toxicity model would probably lead to similar conclusions.

When only secondary impacts are considered, it appears that the remediation of local diesel-contaminated soil results in burdens mainly of a regional scale (bulk wastes). This is due to the significant quantity of asphalt used in the site preparation stage. Asphalt's end-of-life generates a high bulk waste impact during site closure. These results complete the previous LCA studies conducted on bioremediation activities which demonstrated the production of global and local impacts in the same proportion (Page et al. 1999, Volkwein et al. 1999). Aside from the difference of technologies studied and data used, this difference can also be explained by the fact that the impact category 'bulk waste' in the EDIP method is very unique and integrates different elements. This category represents the environmental impacts which can be expected from the occurrence of wastes such as household wastes, construction wastes and the like, once delivered to a controlled municipal landfill. This waste is characterized by the absence of environmentally hazardous substances (Wenzel et al. 2000). Since similar previous studies have not considered the bulk waste category but instead the land-use impact category, it is difficult to compare the results. It is also interesting to observe that transportation of soils to landfills reduces the total impact by 3%. This is due to the low impact of transport emissions compared to bulk waste category. Moreover, it can be stated that transportation of contaminated soil to a landfill is a better alternative than to leave the contaminated soil in place.

4.2 Permanent treatment center

The development of permanent treatment centers offers a good alternative to reduce the environmental burden. Permanent treatment centers' advantages reside in the allocation of the impact of site preparation and site closure to the total quantity of soil treated during the center's operation time, which can be very high (240,000 m^3 for the treatment). If a significant quantity of soil is treated in a permanent treatment center, asphalt paving impact becomes marginal compared to the impact related to routine operations such as soil transportation, monitoring or energy required for pumps. Consequently, site preparation can be more profitable if a significant quantity of soil is treated in a permanent treatment center. However, these soils should be located no further than 200 km (for a site treating 24,000 m^3/year during 10 years). Depending on the volume of contaminated soils treated each year, the duration of permanent installations and the contaminated sites' geographical location, permanent installations can be a very interesting alternative. Before implementing a treatment center, stakeholders have to take into consideration all the parameters cited previously. A prospective LCA appears to be a good means to determine which type of center (permanent or single-use) should be chosen for soil remediation.

5 Conclusion

The results of this study can be used for the reduction of the pollution generated by the remediation of a contaminated site. The following recommendations could be used to improve the environmental performance of aboveground soil bioremediation technology:

- To reduce the environmental impact, hydrocarbon contaminated soil should be treated to achieve the lowest level of residual contaminants.
- If a temporary site cannot be prevented, improvements should be performed as much as possible in the site preparation stage.
- In the site preparation stage, it is suggested to use recycled asphalt instead of virgin asphalt. Whatever the process used to recycle (microwave process, heating, cold mixing), the environmental burden will be lower that the one caused by virgin asphalt production. No environmental data was available for *ex-situ* recycled asphalt at the time of this study. Nevertheless, this improvement option makes sense considering that 50 percent of the asphalt that is removed each year from American roadways is reused in new asphalt pavements (NAPA 2000). Increasing the quantity of asphalt going to the recycling center is another improvement option that is easy to achieve. As it has been shown in this study and in several others (Blomberg 2000, Horvath et al. 1998), concrete paving does not represent a better environmental alternative to asphalt since its impact is higher than asphalt paving. However, in the case of a permanent site, depending on the duration of operation, concrete could be the most environmentally suitable option. Today's concrete pavements typically last longer than asphalt pavements. Moreover, concrete pavement requires less maintenance than asphalt pavement.
- Attention should be paid to the on-site operation of the dozer crawlers and excavators. Reduction of the time of operation of these mechanical equipment (and all other mechanical equipment) could reduce the global impact of the system.
- When applicable, *in-situ* technologies will probably generate less secondary impact than *ex-situ* treatment since no important infrastructures are needed (no asphalt paving for example). However, since the duration of the treatment is always very long and the efficiency low, primary impact would remain and could be a source of concern. A comparative LCA considering both primary and secondary impacts would clarify this point.

6 Recommendation and Outlook

The use of LCA proved to be useful for the assessment of site remediation but has revealed several challenges. First of all, although every attempt has been made at conducting a complete analysis, the overall data quality of the study remains low and thus may limit the conclusions drawn from this analysis. This is particularly true for the geographic specificity of the data. One of the characteristics of the LCA study is that there is only a very general knowledge of site-specific conditions for most of the processes in the product system. Overall, the data quality was not very high (score of 1/3 on the SimaPro 5 data quality scale). This can be explained by the followings facts: 1) Only general (North American or European) data were used for the raw material acquisitions and processes. Even though European processes used in the study are similar to the North American ones (production of HDPE, LDPE, PVC...), the quality of results could improve with more appropriate data; 2) A significant proportion of the data taken from databases is not well documented which considerably reduces the quality score. These two facts probably resulted in an under-estimation of the quality of the data used. Therefore, although the SimaPro quality system awarded a low data quality score, we have confidence in the data used and the results obtained. A comprehensive North-American database with weighting factors should be created to make the future American LCAs more consistent with its geographic context. Likewise, the weighting used in the EDIP method is based on European considerations, not North American ones. An important topic for future application in the field of site remediation will be the integration of site specificities in the LCIA phase, especially for the contaminant's fate and transport according to the physicochemical and geological conditions present. The US EPA recently developed a new US-specific LCIA method named TRACI (Bare et al. 2003). However, the characterization models for the regional and local categories included in TRACI are not applicable to this LCA study because they do not consider the emissions to soil. As in the US, some research has been undertaken in Canada to develop specific Canadian characterization factors for the regional and local impact categories. The current development of an LCIA method specific to the Canadian context will allow the use of Canadian characterization, normalization and weighting factors (Scharnhorst et al. 2004). Also, risk analysis data need to be integrated in the LCIA ecotoxicity and human toxicity models for a more accurate assessment of the primary impact. An improved impact assessment would allow a much accurate comparison between primary and secondary impacts and thus, provide better guidance for the decision makers.

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